

# A development of computer vision elements for processing the results of tensile tests of specimens and building diagrams of ultimate plasticity

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**Abstract.** The use of specimens with a round notch allows expanding the application of tensile tests in order to study the ultimate plasticity of materials. However the main difficulty in processing the results of experiments is the need to measure the radius of curvature of the neck and the diameter in the minimum cross-section of the specimen. These dimensions determine a stress triaxiality value of the material in the center of the neck according to the Bridgman model or the other ones. This article is devoted to the development of elements of a computer vision system designed to measure the neck, which is formed both on cylindrical specimens and on specimens with a notch. To extract the contour of the specimen and to measure the forming neck, the video recording of the test process on a digital single-lens reflex (DSLR) camera is used. The paper proposes a method for recording the test process using the background, which allows to increase the accuracy of determining the contour of the specimen during subsequent image processing. The Sobel filter is used to extract the contour of the specimen, and a special neck profile equation allows to determine the neck dimensions.

## 1. Introduction

The ability to predict the moment of ductile fracture of materials is very important for solving practical problems of metal forming, as well as for creating adequate computer models of technological processes and products – digital twins. The value of the material ultimate plasticity is quantitatively characterized by the strain value accumulated up to the time of fracture. The plasticity of the material depends on temperature, strain rate, external hydrostatic pressure, Lode angle, and also the metal stresses value in the deformation zone. There are many criteria in literature that can be used to predict the ductile fracture moment [1–5]. Johnson-Cook and Cockcroft-Latham are the most popular of them. Despite the influence of many factors, the ultimate plasticity of materials is usually estimated in simple tests, which provide a uniform distribution of stresses and strains throughout the sample and a constant value of a stress state index. Such tests in particular include the extension of cylindrical specimens. However, after localization of deformation in the neck, the stress state of the metal becomes triaxial and must be taken into account to increase the accuracy of fracture models identification.

Another limitation of tensile tests of cylindrical specimens is the inability to change the stress triaxiality over a wide range of values, while it differs significantly for most technological processes of metal forming. For example, when pressing various profiles, compressive stresses prevail, and when drawing wires, tensile stresses prevail. The stress triaxiality values are defined as following:



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$$\eta = \frac{\sigma}{\sigma_{eq}}, \quad (1)$$

where  $\sigma$  is the mean normal stress and  $\sigma_{eq}$  the equivalent von Mises stress. The use of specimens with different notches while studying the materials plasticity allows you to extend the range of stress triaxiality values [5–6]. However, the change in this parameter during tensile tests must also be taken into account to increase the accuracy of fracture models identification.

In [7], Bridgman showed a relationship between the stress triaxiality value in the minimum cross-section of specimen and the geometry of the neck:

$$\eta = \frac{1}{3} + \ln\left(1 + \frac{d}{4R}\right), \quad (2)$$

where  $d$  is the minimum cross-sectional diameter of the neck and  $R$  the radius of its curvature. In addition to the Bridgman model, other models of stress distribution in the neck are presented in the literature [8–9]. However, they also derive that the stress triaxiality is determined by the geometry of the neck. Thus, the need to take into account the stress triaxiality value as well as its change while identifying materials fracture models poses the problem of measuring the neck profile of cylindrical and notched specimens during the test process.

In works [10–11], La Rosa and Mirone have proposed a material-independent necking model without the need of experimental profile curvature measurement. However, this model does not take into account the influence of the hardening curve of a wide range of materials on the change in the neck. Therefore, the use of this model must be preceded by numerous experimental confirmations.

Focusing on the methods that use the experimental measurement of neck profile, several approaches have been proposed in [6, 12–13]. In [12], G'Shell et al. applied a tensile testing system with the computer-aided video extensometer and a true strain-rate controller. To analyze the neck profile, this system used frames of 512×512 pixels. In [6], Sancho et al. have used a single DSLR camera and an automated image processing algorithm for neck profile extraction. In order to optimize the sharpness of images, authors applied an additional light focused on specimens painted in white. In [13], they proposed an improved test procedure that used only one backlight placed behind the specimen.

In this paper, we propose our own approach to computer-aided measurement of the neck profile while testing cylindrical and notched specimens in order to determine the radius of neck curvature and the minimum diameter of the specimen in the neck.

## 2. The analytical description of the neck profile while testing notched specimens

The choice of an analytical expression for describing the functional dependence of the radial coordinate of points on specimen surface  $\rho$  on the corresponding axial coordinate  $z$  is an important step in the development of a computer-aided system aimed for constructing ultimate plasticity diagrams. Fitted equation of the neck profile allows you to calculate the radius of the neck curvature in the minimum cross-section with the use of the first curvature of a space curve at a point:

$$R = \frac{\left[1 + (\rho'(z_0))^2\right]^{\frac{3}{2}}}{|\rho''(z_0)|}, \quad (3)$$

where  $\rho'(z_0)$  and  $\rho''(z_0)$  are the first and second derivatives of the neck profile equation,  $z_0 = 0$  is the axial coordinate of minimum cross-section.

In work [10], La Rosa and Mirone have proposed fitting techniques that use the approximation of the neck profile by way of second or third order polynomials. Nevertheless, in this paper, it is proposed to use a special type of equation, which, as shown in [14], describes the profile of necked cylindrical specimen along the entire gauge length rather well:

$$\rho = \frac{d_1}{2} - \frac{d_1 - d}{2} \cdot \left(1 + \frac{z^2}{c}\right)^{-1}, \quad (4)$$

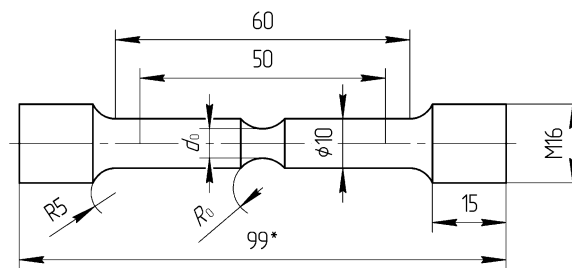
where  $\rho$  and  $z$  are radial and axial coordinates of points on surface of specimen respectively,  $c$  is the parameter sensitive to material properties,  $d$  – the minimum neck diameter and  $d_1$  – the diameter of the specimen at the beginning of necking.

It should be noted that equation (4) does not allow approximating the entire surface of the notched specimen, in the smallest section of which the neck is formed. However, the graph of equation (4) has exactly two inflection points between which the neck is approximated by the proposed equation with high accuracy.

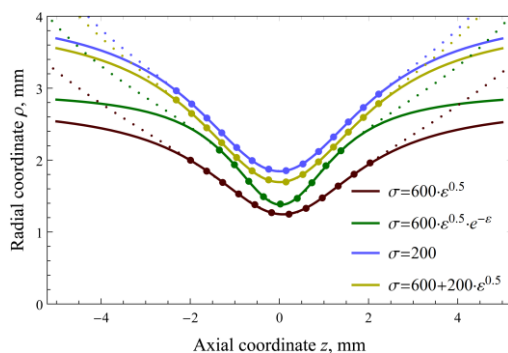
In this work, to estimate the accuracy of the neck profile approximation, the computer simulation has been performed in the Deform-2D software. We studied the shape change of the neck on standard five-fold specimens (according to the Russian state standard GOST no. 1497), as well as specimens having a radial notch according to figure 1. The dimensions of the notched specimens are listed in table 1.

**Table 1.** Characteristics of the analysed specimens.

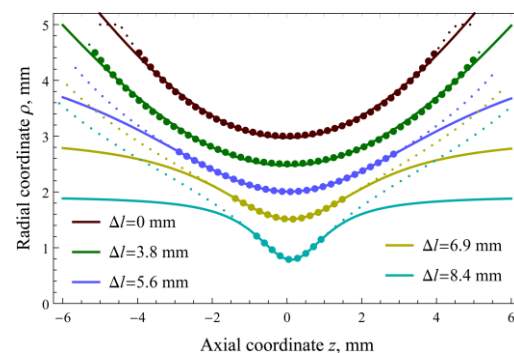
Specimen number	Specimen characteristics	Notch acuity, $d_0/R_0$	Curvature, $R_0$ (mm)	Diameter, $d_0$ (mm)	Theoretical triaxiality, $\eta_0$
1	Smooth specimen	0	$\infty$		0.333
2		0.5	12	6	0.451
3	Notched specimen	1	6		0.556
4		2	3		0.739



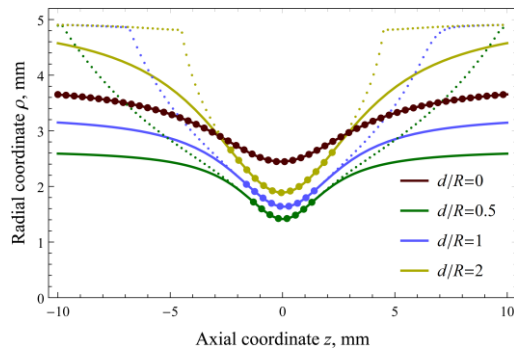
**Figure 1.** The geometry of specimens having the round notch.



**Figure 2.** The comparison of fitted curves with FEM results for specimen with notch acuity 1, made from materials with different stress-strain curve.



**Figure 3.** The comparison of fitted curves with FEM results for specimen with notch acuity 1, made from material with stress-strain curve  $\sigma = 600 \cdot \varepsilon^{0.5}$  for different instants of test.



**Figure 4.** The comparison of fitted curves with FEM results for specimens with different notch acuity, made from material with stress-strain curve  $\sigma = 600 \cdot \varepsilon^{0.5}$ .

Figures 2–4 represent graphs of approximating curves according to equation (4). These curves are shown by continuous lines in comparison with the actual neck profiles that are shown by points and found during computer simulation. Large dots on these figures correspond to the points on the specimen surface that were only used to approximate the neck profile.

The results of computer simulation show that a high accuracy of the neck profile approximation is achieved when you use the only points on the specimen surface lied between the inflections. This is true in the case of using materials with different hardening curves (figure 2), for any instant of the test (figure 3), as well as when using specimens with different notch acuity (figure 4). Hardening curves of test materials are shown in figure 2.

The approximation accuracy was estimated as the maximum difference between the actual radial coordinate of any point on the specimen surface and the corresponding calculated value in accordance with the fitted equation (4). According to figure 2, the maximum difference was 0.018 mm; according to figure 3–0.11 mm; according to figure 4–0.05 mm. The maximum error occurs at the beginning of the test of the notch specimens, when the neck is still not evident. However, the error value is rather small.

### 3. The computer vision system for measuring the neck profile

The computer vision systems are being used today in a wide variety of real-world applications [15], which include, for example, optical character recognition, machine inspection, automotive safety, fingerprint recognition, face detection, etc. An automated edge detection is one of them which allows performing quantitative image analysis.

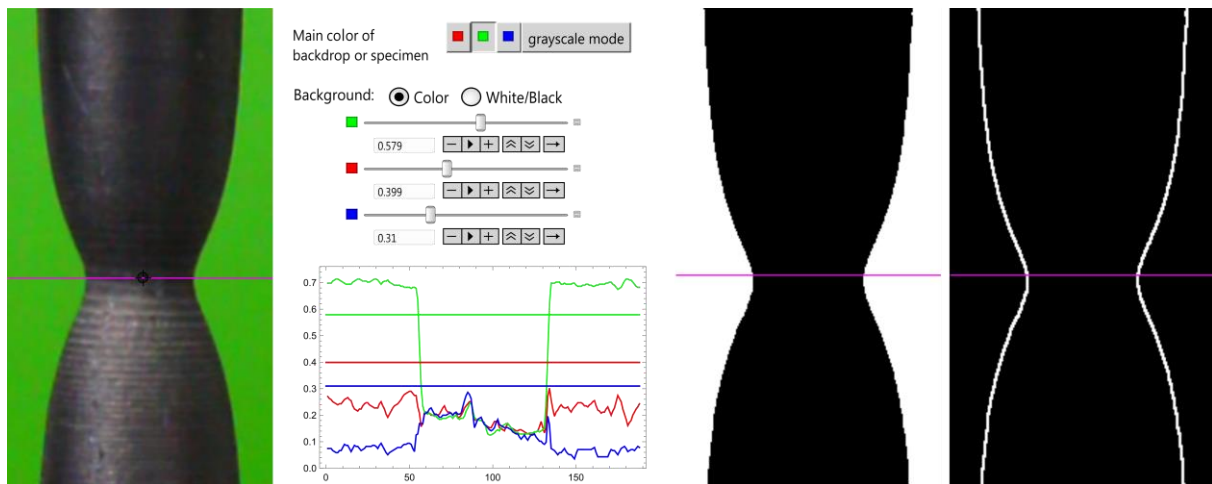
#### 3.1. Neck profile extraction

The use of optical measurement systems is a good solution for obtaining neck size data during the test for a number of reasons. Firstly, you get the results of a neck measurement without the need to remove a specimen from the grips of a test setup. Secondly, the number and accuracy of measurements are determined by the algorithms for obtaining and processing images that are embedded in the computer vision system. At the same time, the influence of the human factor on the accuracy of the data obtained is reduced. Finally, the speed of processing the test results increases significantly.

In this work, we have developed a system for optical measurement of the neck profile, which is also formed on specimens with a notch. To obtain the coordinates of the points corresponding to the specimen surface, we use a single DSLR camera Canon 700D. In the case of testing specimens with a notch, when the neck size changes quickly, the test process is better to record in a video file. Extracting individual frames from a video file is carried out using the FFmpeg software. For automated processing of a large number of individual frames, a specialized program is written in the Wolfram Language.

Extracting the contour of the neck consists of several stages. At the first stage, on each frame, an area is defined on which a specimen is necked. At the second stage, the specimen axis is searched and the image is rotated so that the axis found coincides with the vertical. At the third stage, a filter is applied to separate the specimen from the background. Finally, the neck contour is extracted and the received data is processed.

One of the most difficult for the software implementation is the filtering algorithm that allows you to separate the specimen from the background. To increase the contrast of the image and the accuracy of the edge detection, a colored backdrop can be used. The program provides various background options – the commonly used green backdrop, the blue, red, the black or the white ones. In the last two cases, the recording of the test process can be carried out similarly to [6] and [13], when the specimen is painted or backlighted, respectively. Figure 5 represents an example of the own chroma key filter tuning. The filter is tuned by several manipulators that set the illumination levels of the background or specimen for each color channel separately or together (grayscale mode) depending on the user's choice.



**Figure 5.** The tuning of the chroma key filter.

To extract neck profile, the image with a previously removed background is subjected to binarization, and then to processing by the gradient filter. We have considered the possibility of applying different gradient filters such as Prewitt, Sobel and Scharr, which differ in the coefficients of the convolution mask. It is established that the Sobel filter provides the most accurate result. In addition, a convolution mask with a size of  $3 \times 3$  pixels provides white coloring of two pixels located around the actual specimen surface from different sides. One pixel is located on the side of the specimen, and the other one on the side of the background. Further, the approximation of white pixels using the proposed equation (4) and the least-squares technique is carried out in such a way that the fitted curve is located between the indicated white pixels, i.e. closest to the actual specimen surface. This approach is an alternative to the sub-pixel accuracy algorithm [13].

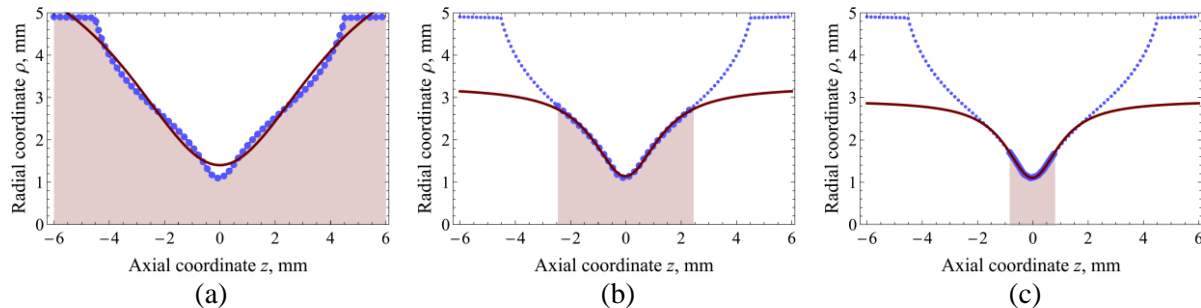
### 3.2. Refining the boundaries of the neck used for approximation

The results of computer simulation of tensile testing of the specimens with a round notch have shown that only those points on the specimen surface that are located between the nearest inflections should be used in order to achieve the most accurate neck profile approximation. The presence of only two inflection points in the graph of equation (4) makes it possible to carry out an automatic iterative search of the “neck boundaries” which is a part of the specimen surface only used for approximation. To do this, it is necessary to minimize the difference between the axial coordinates of the neck boundaries  $z_b$  and the axial coordinates of the inflection points:

$$z_b - \left(\frac{c}{3}\right)^{1/2} \rightarrow \min. \quad (5)$$

In this work, the entire surface of the specimen part indicated on the frames previously as the region of interest is used for approximation in the first iteration. The found value of the parameter  $c$ ,

which is included in equation (4), allows to calculate the axial coordinates of the inflection points and compare them with the boundaries of the neck. For subsequent iterations of approximation, only those surface points are used that are between the calculated inflection points. The approximation procedure is repeated until the neck boundaries in the notch become inflection points of equation (4) with a given accuracy. Figure 6 presents an example of such an iteration.



**Figure 6.** Automatic search for “neck boundaries” based on the coordinates of the inflection points: (a) the first iteration, (b) the second iteration, (c) the third iteration.

#### 4. Conclusions

The measurement of the radius of curvature and the diameter of specimen in the minimum cross section of the neck is based on the approximation of experimental data using the proposed equation. The study has shown that the proposed equation is effective. To automate the processing of video records of the test process and the measuring of the neck, the program is developed in the Wolfram Language. The program for processing the test results includes algorithms widely used in computer vision systems. This program is able to determine the profile of the neck, which is formed both on cylindrical specimens and on specimens with a radial notch at any instant of the test. The found dimensions of the neck are necessary for building diagrams of the materials ultimate plasticity.

#### Acknowledgments

This work was supported by the grant MK–1878.2020.8 from the President of the Russian Federation for young scientists – candidates of sciences.

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